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FORTY-YEAR DEVELOPMENT OF DOUGLAS-FIR STANDS PLANTED AT VARIOUS SPACINGS

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CONTENTS

INTRODUCTION

As the need for intensive management of timberlands becomes more evident, the effect of initial plantation spacing and/or early thinning on subsequent stand development is of increasing interest and importance to the land manager. Douglas-fir stands planted in 1925 at Wind River, near Carson, Wash., have been observed periodically for over 40 years and provide an increasingly valuable record of benefits derived from fairly wide, uniform spacing. Earlier results were reported by Isaac (1937), Munger (1946), Eversole (1955), Reukema (1959), and Morse.[1/]

During recent years, diameter and height growth of even the 100 largest trees per acre and total basal area and cubic volume growth per acre have all been substantially greater on the wider spacings. Furthermore, a great share of the total volume produced in the closer spacings is not merchantable.

THE STUDY

Study Area

The spacing test plantations occupy a site IV alluvial flat at an elevation of about 1,350 feet. The soil is a loose sandy loam with sporadic admixture of basaltic gravel and cobble. This juvenile soil is developing on pumiceous alluvium which is generally 4 to 7 feet deep and underlain by lightly fractured, basaltic rock.[2/] Felled timber on the area was accidentally burned in 1920, after which all usable material was salvaged. In 1924, the area was reburned by a very intense fire that destroyed all reproduction and burned all duff and debris down to mineral soil.

Treatment

In the spring of 1925, 1-1 seedlings were planted in 2.8-acre blocks at spacings of 4 by 4, 5 by 5, 6 by 6, 8 by 8, and 10 by 10 feet. A 0.5-acre block was planted with surplus stock at 12- by 12-foot spacing. These seedlings were started in the Wind River Nursery from seed of an unknown source near Roy, Wash. Extra seedlings were held in the nursery for subsequent replacement of failures.

[1/] Morse, J. E. An economic model for optimum initial spacing in forest plantations. 226 pp. 1962. (Unpublished M.F. thesis on file at College of Forestry, New York State Univ., Syracuse, N.Y.)

[2/] Personal communication with Richard E. Miller, Soil Scientist, Pacific Northwest Forest & Range Experiment Station, Olympia, Wash.

Sampling and Measurements

Different sampling systems were used as the study progressed, introducing some inconsistencies in reported results. At ages 7, 12, and 17 (years from seed germination), seedling heights were measured on selected rows of trees throughout each spacing. At age 23 (1945), three 1/4-acre plots were established in each spacing, except the 12 by 12 which contains a single 0.4-acre plot (fig. 1). In that year, diameters were measured on all trees on plots in the 8 by 8 through 12 by 12 spacings, but on only a systematic sample of rows on plots in the 4 by 4 through 6 by 6 spacings. At age 29 (1951) and subsequently, diameters of all trees in each plot were measured. Also in 1951, plot 17 was added in the 8 by 8 spacing as a substitute for plot 12, which was thought to be on lower quality site. Heights since 1945 have been measured on varying numbers of trees (minimum of 10 per plot) distributed across the entire d.b.h. range.

All volumes for the period 1945-65 were recomputed by means of tarif equations developed by Turnbull and Hoyer (1965). Average tarif numbers for each spacing and period were determined from trees measured for height; these averages were then smoothed over time to remove inconsistencies due to different samples measured. It was assumed, but not confirmed, that bole-form of trees of a given d.b.h. and height had not been influenced by spacing.

Other measurements have also been made on these plots. Crown dimensions were measured on selected trees at ages 12 through 29. In 1967, crown and stem dimensions were measured on about 36 trees for each spacing, equally distributed among plots and across the d.b.h. range therein, to determine the effect of spacing on stem-crown relationships. Results of this study are reported by Curtis and Reukema.[3/] Also in 1967, locations of all trees on plots plus 20-foot buffer strips were stem-mapped.

RESULTS AND DISCUSSION

Primary interest centers around the effect of spacing on usable yield. However, because merchantability standards vary, emphasis was placed on total yield, supplemented by *examples* of spacing effects on merchantable yield. Stand growth and yield will be discussed first, followed by discussion of their component parts--mortality and individual tree diameter and height growth.

Although the subject of this paper is stand development over the 41 years since planting seedlings, emphasis is placed on development during the most recent 14 years (ages 29-43), which clearly illustrates current trends. Earlier data, based on different sampling systems, are not directly comparable.

[3/] Robert O. Curtis and Donald L. Reukema. Crown development and site estimates in a Douglas-fir plantation spacing test. (Submitted to Forest Science for publication.)

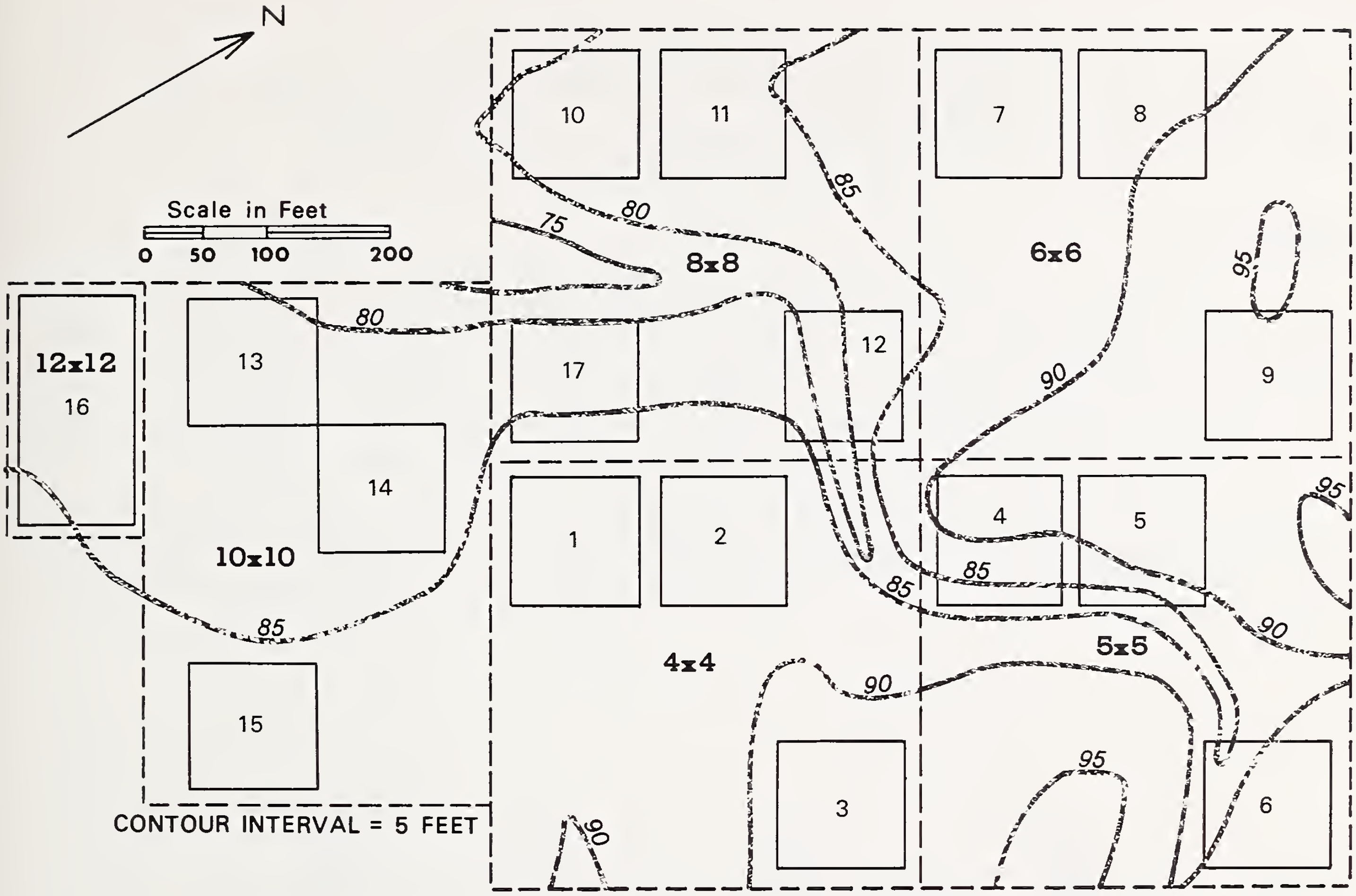

Figure 1.—Layout of Wind River Douglas-fir plantation spacing test.

Readers desiring information on how these findings relate to the general body of knowledge on spacing effects are referred to reviews by Reukema (1967) and by Sjolte-Jorgensen (1967). It is sufficient here to say that, although these results are contrary to widely accepted hypotheses, they support an increasing body of evidence that it may be commonplace for maximum production on low site-quality land to be attained through much wider than normal spacing of trees.

Growth and Yield

There have been fairly clear trends of increasing stand growth with decreasing stand density (number of trees), especially during the last 5 years. These general trends are elaborated in the succeeding sections. Differences in average tree dimensions and stand productivity among plots within spacings probably result from a combination of localized variations in site quality and in past injuries and mortality influencing stand density, stocking, and development.

Although the area is believed to be of quite uniform site quality, there are apparent minor local variations. There is no indication of any gradient across spacings, but there is considerable evidence that all 8 by 8 plots have somewhat lower than average site quality. In figures which follow, individual

plot values provide an index of variability. Superimposed on these bar graphs are curves which the author believes illustrate probable *trends* of production relative to spacing. Rather than passing through spacing averages, these curves reflect modification due to the aforementioned local variations.

Basal Area

Although *gross* basal-area yield per acre has always decreased with increasing spacing (fig. 2), the difference between the 4 by 4 and 12 by 12 spacings has narrowed from about 51 square feet at age 29 (1951) to 36 square feet at age 43 (1965). Widely spaced stands are currently growing more rapidly, so the difference should continue to lessen. During the 1960-65 period, gross basal-area growth was about 59 percent greater in the 12 by 12 than in the 4 by 4 spacing. Because of much greater mortality in close spacings, *net* basal-area yield is currently quite similar in all spacings, decreasing only slightly with increasing spacing.

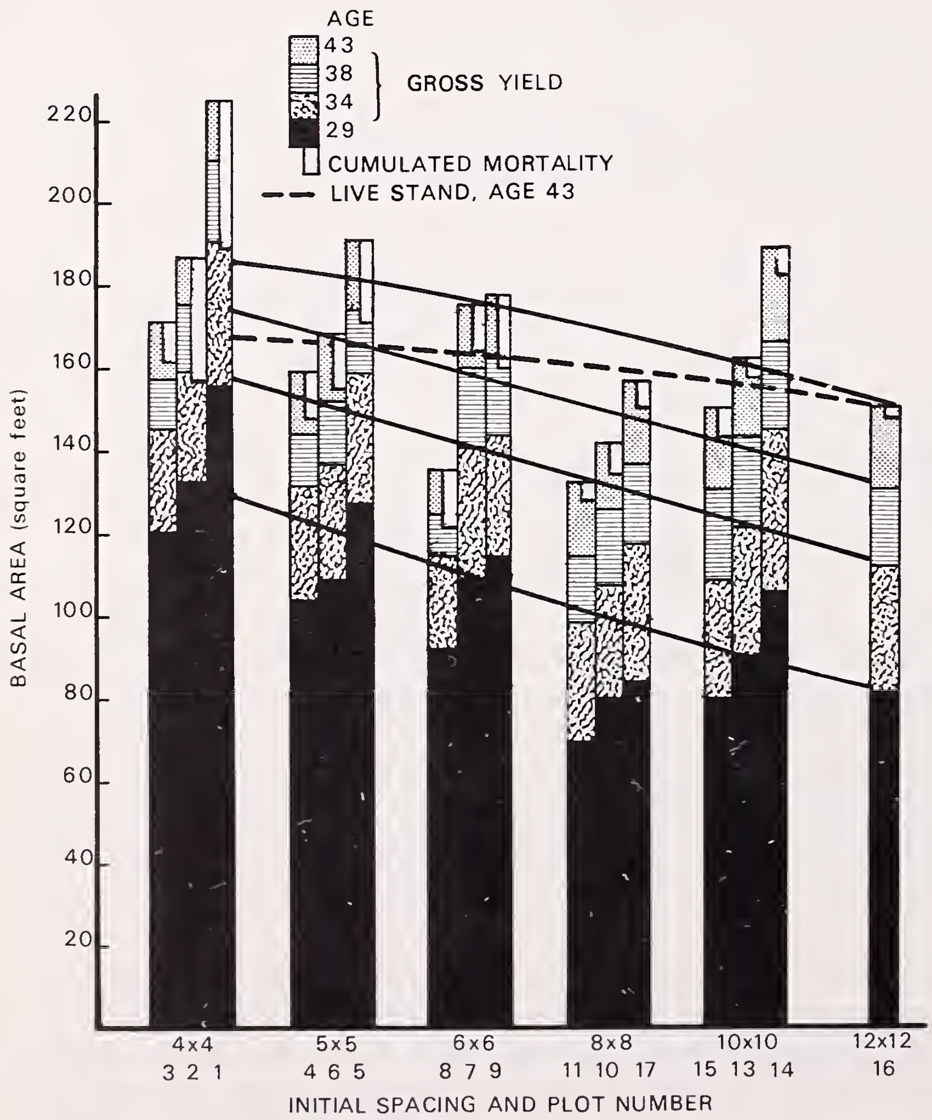

Figure 2.—Effect of spacing on basal-area yield per acre, by periods. (Gross yield at age 43 minus cumulated mortality = net yield.)

Cubic Volume

Gross cubic-volume yield at age 29 also decreased with increasing spacing (fig. 3). However, because of more rapid height growth on wider spacings, differences among spacings in volume growth have been greater than those in basal-area growth. Gross cubic-volume growth since age 29 has averaged about 70 percent greater in the 12 by 12 than in the 4 by 4 spacing. During the most recent period, gross cubic-volume growth was about 117 percent greater in the 12 by 12 than in the 4 by 4 spacing; differences between the 10 by 10 and 12 by 12 appear negligible. Thus, total gross cubic-volume yield of all trees 1.5-inch d.b.h. and larger (CVTS) now tends to *increase* with increased spacing. Total gross cubic-volume yield at age 43 was about 18 percent greater in the 12 by 12 than in the median 4 by 4 spacing (4,775 vs. 4,060 cubic feet). Whereas, gross mean annual increment is now apparently near culmination on close spacings, it is still increasing substantially on wide spacings (table 1). The sharp decline in periodic annual increment on all spacings during the most recent period is probably due largely to climatic influences.

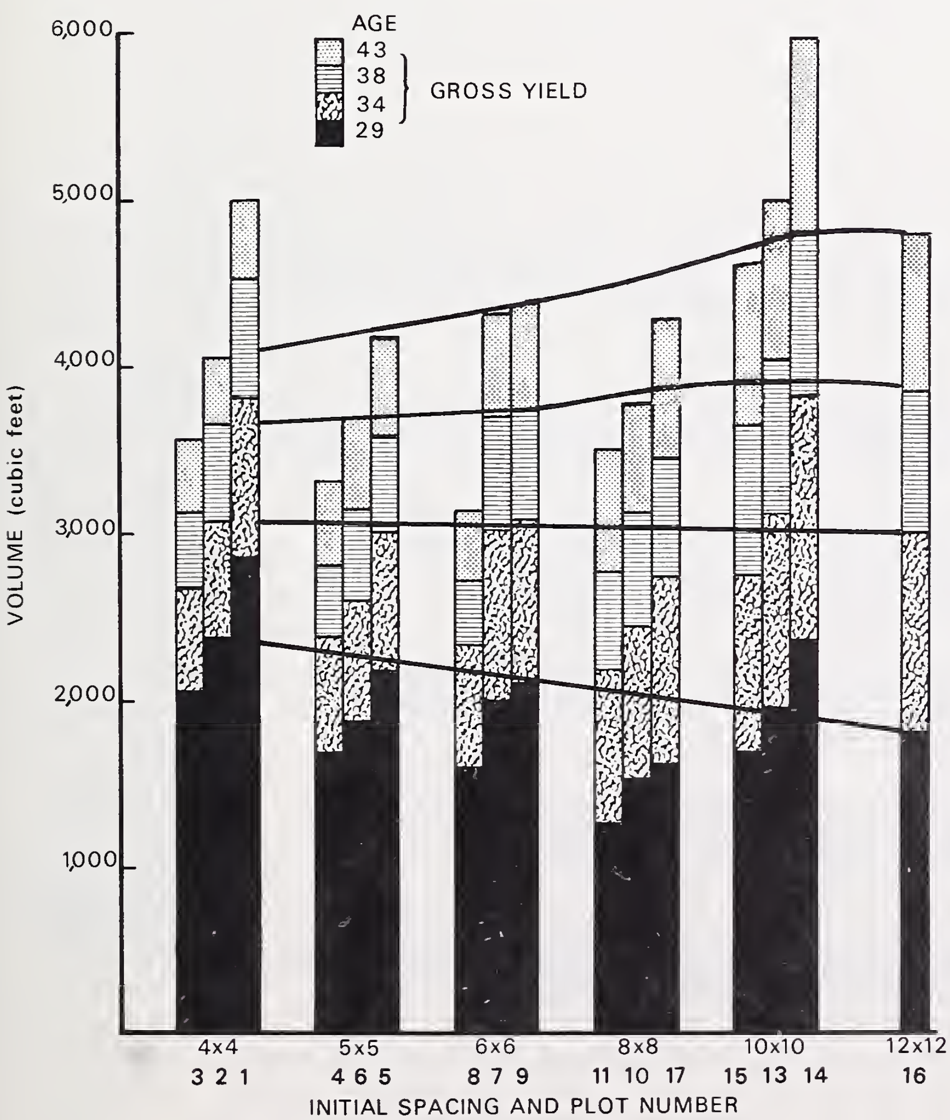

Figure 3.—Effect of spacing on total cubic-volume yield per acre, by periods.

Table 1.--*Gross periodic annual and mean annual increment,*

Wind River spacing test

Spacing (feet)	Periodic annual increment by age				Mean annual increment by age				
	23-29	29-34	34-38	38-43	23	29	34	38	43
	Cubic volume per acre[1/]								
4 by 4	150	151	156	82	67	84	94	99	98
5 by 5	150	151	138	106	44	66	78	84	87
6 by 6	156	183	154	106	42	66	83	89	92
8 by 8	133	196	176	141	26	51	72	82	90
10 by 10	198	244	252	195	35	69	95	110	121
12 by 12	178	238	225	179	32	62	88	101	111

1/ Average increment on plots representing each spacing.

If current growth trends continue, the difference in gross yield will continue to increase in favor of wide spacings. Because of heavier mortality on the closer spacings, increase in net cubic-volume yield with increased spacing is even greater. This indicates the superiority of wide spacings, no matter what merchantability standards may be applicable.

Merchantable Volume

When we impose merchantability standards, the economic advantages of wider spacings become even more impressive (figs. 4 and 5). If we use volume to a 4-inch top of trees larger than 5.6-inch d.b.h. as a minimum standard, current merchantable volume (CV4) ranges from about 1,500 cubic feet on the 4 by 4 to 4,350 cubic feet on the 12 by 12 spacing. About 58 percent of the live volume on the 4 by 4 spacing is nonmerchantable, compared with only 8 percent on the 12 by 12; corresponding nonmerchantable volumes are 2,750 and 430 cubic feet. Although most of the current growth in all spacings is now being added to merchantable volume, past nonmerchantable production is mostly lost. If we use a larger minimum top diameter as a standard, a greater portion of the total volume is, of course, nonmerchantable. For example, with a 6-inch top limit (CV6), 92 percent of the volume on the 4 by 4 as against 22 percent on the 12 by 12 is currently nonmerchantable.

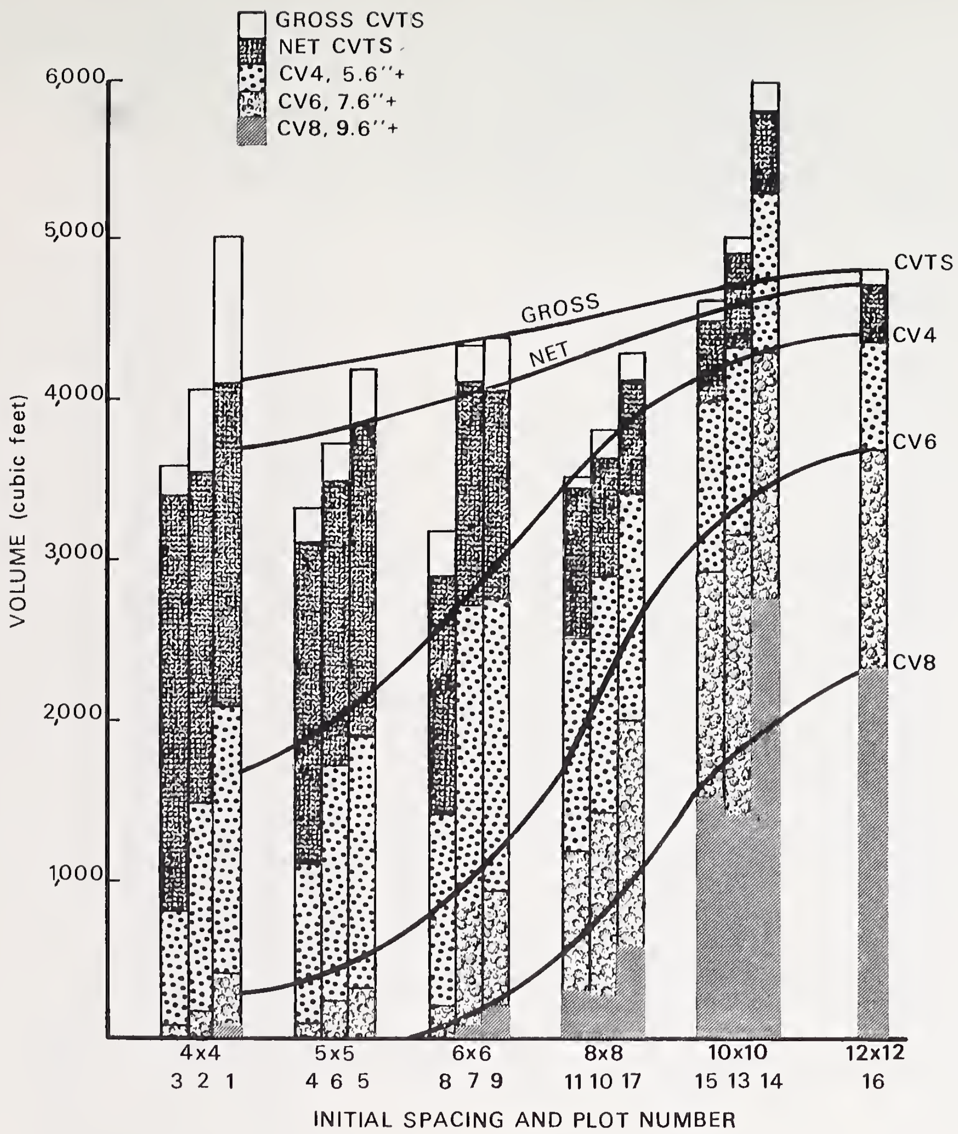

Figure 4.—Effect of spacing on total and merchantable cubic-volume yield per acre at age 43.

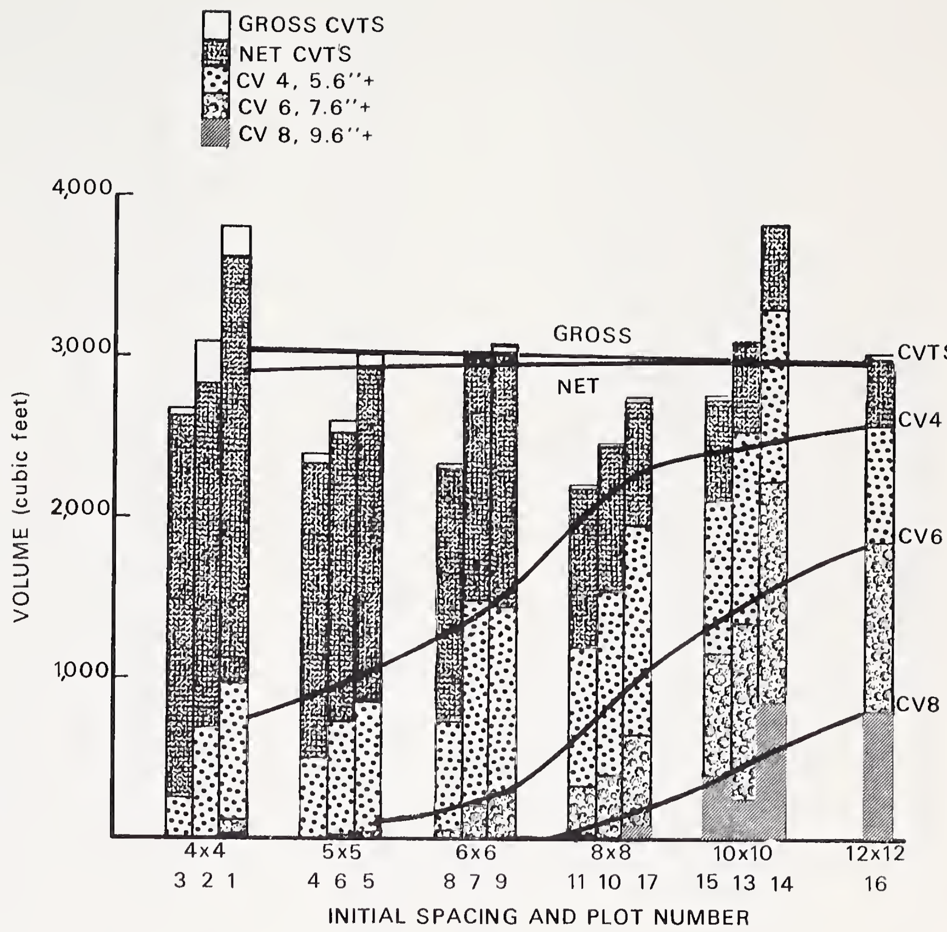

Figure 5.—Effect of spacing on total and merchantable cubic-volume yield per acre at age 34.

(CVTS = cubic volume of the total stem of all trees 1.5-inch d.b.h. and larger; CV4 = cubic volume to a 4-inch top of trees 5.6-inch d.b.h. and larger; CV6 = cubic volume to a 6-inch top of trees 7.6-inch d.b.h. and larger; CV8 = cubic volume to an 8-inch top of trees 9.6-inch d.b.h. and larger.)

Mortality and Damage

First 5 Years

Due to heavy initial mortality, replacements were necessary for 5 consecutive years (1926-30) following planting (table 2). The first year, 36 percent of the seedlings died and were replaced. Many of the seedlings planted subsequently were to replace initial replacements, as there were spots, on ashy or shallow soil, where mortality occurred repeatedly.[4/] Unfortunately, we do not have a record of these locations.

After Stand Establishment

Occurrence of mortality and damage over the subsequent 36-year period was quite erratic, but totals do show a clear relationship to spacing.

Trees lost ranged from 15 percent on the 12 by 12 spacing to more than 25 percent on the closer spacings (table 3). Unfortunately, mortality occurring between ages 17 and 23 could only be estimated by subtracting number of live trees at age 23 plus mortality between ages 7 and 17 from the theoretical number planted. The resulting high estimate of mortality in the 4 by 4 spacing in the age 17-23 period probably reflects inconsistencies in number of trees planted rather than actual mortality.[5/]

During the most recent 20 years (1945-65), the portion lost was about twice as great on the 6 by 6 and closer spacings as on 8 by 8 and wider spacings, ranging from 9.1 percent on the 12 by 12 to 20.7 percent on the 4 by 4.

In addition to this mortality, the stands contain many damaged live trees. An average of 22 percent of the trees alive in 1965 had at some time suffered damage, mostly during the most recent period. The range, by plots, was 20 to 33 percent on the 4 by 4 through 6 by 6 spacings and 7 to 11 percent on the 8 by 8 through 12 by 12. The fact that not only the number but also the *proportion* of dead and damaged trees increases substantially with increasing number of trees, or closer spacing, indicates that the closely spaced trees are much more *susceptible* to damage and death than are widely spaced trees.

[4/] Leo A. Isaac and George S. Meagher. Progress Report No. 2, Spacing in Douglas-fir plantations. 1936. (Unpublished report on file at Pacific Northwest Forest & Range Exp. Sta., Olympia, Wash.)

[5/] If number of trees actually planted were 450-500 per acre less than the theoretical 2,722 (i.e., about 4.4-foot vs. 4.0-foot spacing), estimated losses would fall in line. This is a reasonable discrepancy when one plants at such close spacings.

Table 2.--*Replacements during first 5 years to maintain spacing, Wind River spacing test*

Year	Percent	Number	Suspected principal cause of mortality
1926	36	7,200	Drought
1927	17	3,300	Drought
1928	5	1,000	Drought
1929	4	730	Stock too large
1930	3	630	Shoestring fungus

Table 3.--*Distribution of mortality by spacing and age, 1930-65, Wind River spacing test*[1/]

Initial spacing (feet)	Age (years)							
	7-12	12-17	17-23	23-29	29-34	34-38	38-43	Total
	- - - - - - - - - *Number of dead trees per acre* - - - - - - - - -							
4 by 4	166	30	514	147	141	55	217	1,270
5 by 5	78	12	31	37	100	45	132	435
6 by 6	59	18	39	30	33	19	136	334
8 by 8	42	14	16	5	16	7	44	144
10 by 10	17	5	5	4	4	7	30	72
12 by 12	2	0	0	8	3	3	15	31
	- - - - - - - - *Percent of original number planted* - - - - - - - -							
4 by 4	6.1	1.1	18.9	5.4	5.2	2.0	8.0	46.7
5 by 5	4.5	.7	1.8	2.1	5.7	2.6	7.6	25.0
6 by 6	4.9	1.5	3.2	2.5	2.7	1.6	11.2	27.6
8 by 8	6.1	2.0	2.4	.7	2.3	1.0	6.5	21.0
10 by 10	4.0	1.1	1.1	.9	.9	1.6	6.9	16.5
12 by 12	5.0	0	0	2.6	1.0	1.0	5.0	14.6

[1/] Mortality occurring between ages 7 and 17 was estimated by a sampling of selected rows throughout the plantation, and that between ages 23 and 43 was recorded on permanent sample plots. Mortality between ages 17 and 23 was determined by subtraction from theoretical number planted.

Apparent Causes

Averaged for all spacings, 61 percent of all mortality during the last 20 years has been attributed to storm damage (breakage, bending, windthrow), 7 percent to normal suppression, and 2 percent to root rot *(Poria weirii)* (table 4). The causes of the remaining 30 percent have not been specified.[6] Much was probably due to normal suppression; some was almost certainly due to storm damage. Possible association between storm damage and root rot as causes of mortality on these plots has not been assessed. Of the damaged *live* trees, 97 percent have been broken or bent by storms. The remainder have dead tops or sickly crowns.

Distribution by Tree Size and Crown Class

Mortality and damage were generally confined to lower crown class trees which had not reached a merchantable size. Average d.b.h. of dead trees, by spacing, ranged from 3.1 inches on the 4 by 4 and 5 by 5 to 4.9 inches on the 10 by 10. An average of only six trees per acre were of merchantable size (5.6-inch d.b.h. or larger) at the time they died. Similarly, an average of only 12 damaged live trees were of merchantable size. Distribution of these merchantable trees showed no relationship with spacing.

In an assessment of distribution of mortality and damage by crown class, it is appropriate to look at data for the most recent period (1960-65), since the bulk of mortality and damage occurred during this period. On the average, 18 percent of the previously undamaged live trees suffered storm damage during that time. Damage was more extensive than this in the closer spacings and less in the wider spacings (table 5). Distribution of total damage among crown classes was similar in all spacings, averaging 3 percent dominants, 28 percent codominants, 45 percent intermediates, and 23 percent suppressed. Expressed as a percent of previously undamaged trees, damage on the closer spacings was about equally distributed across the codominant, intermediate, and suppressed crown classes.

About 40 percent of the trees first damaged during the 1960-65 period had died by 1965. Many of the live damaged trees are expected to die during the next period, whereas some certainly will linger on and/or recover. Trees which died during this period as a result of current damage accounted for 67 percent of the total mortality in this period. The remaining 33 percent was primarily a result of previous damage; a little was due to normal suppression.

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[6] Very little of this unspecified mortality is recent; 53 percent occurred during the period 1945-51 and another 32 percent during 1951-56.

Table 4.--*Summary of mortality and damage during the last 20 years, by spacing and cause, Wind River spacing test*

Condition	Initial spacing in feet					
	4 by 4	5 by 5	6 by 6	8 by 8	10 by 10	12 by 12
	Number of trees per acre					
Dead:						
Broken	175	155	137	38	36	18
Bent or leaning	62	44	7	7	1	0
Uprooted	22	18	33	9	0	2
Suppression	46	15	13	3	1	2
Root rot	20	1	4	1	0	0
Unspecified	239	80	23	15	7	5
Total	564	313	217	73	45	27
Damaged:						
Broken	22	42	42	18	26	15
Bent or leaning	367	238	153	28	4	2
Sickly or dead top	7	6	5	1	1	5
Total	396	286	200	47	31	22

Table 5.--*Distribution among crown classes of trees first damaged during the period 1960-65, by spacing, Wind River spacing test*

Initial spacing (feet)	1960 crown class				
	Dominant	Codominant	Intermediate	Suppressed	Total
	Number of trees per acre				
4 by 4	20	132	203	92	447
5 by 5	5	91	92	92	280
6 by 6	5	49	105	31	190
8 by 8	1	3	26	10	40
10 by 10	1	8	16	4	29
12 by 12	0	0	7	0	7
	Percent of previously undamaged trees				
4 by 4	9	33	26	20	24
5 by 5	2	24	18	22	18
6 by 6	2	20	29	14	18
8 by 8	1	2	11	17	7
10 by 10	1	6	14	40	7
12 by 12	0	0	10	--	3

Impact on Growth and Yield

Because of the small size of most dead trees, the direct impact of mortality on volume yield to date has been rather slight. Losses during the 20-year period 1945-65, by spacing averages, amounted to only 1 to 12 percent of the total cubic-volume yield. However, the indirect impact of mortality and damage on growth capabilities and yield should not be dismissed. In the wider spacings, damage and mortality generally befell individual trees scattered through the stand--perhaps a beneficial natural thinning. In the close spacings, on the other hand, damage and mortality tended to occur in a clumpwise pattern, typically resulting from chain-reaction windthrow and breakage (fig. 6). Thus, openings created in the close spacings tended to be much larger than those in the wider spacings and took more area out of production. Furthermore, in close spacings, trees surrounding these openings have less vigorous crowns than those in wide spacings, so have been less able to respond to release received from these natural openings.

Figure 6.—Clumped damage was a common occurrence in the closer spacings (left), whereas there was little damage in the wider spacings (right).

Individual Tree Development

Diameter

As would be expected, average d.b.h. of all trees 1.5 inches and larger was much smaller in close spacings than in wider spacings. But how has spacing influenced development of the largest trees in these stands? Average d.b.h.[7] of the 100 largest trees per acre is commonly used as a measure of this effect. At age 29 (1951), average d.b.h. of the 100 largest trees per acre was 56 percent greater in the 12 by 12 than in the 4 by 4 spacing (8.9 vs. 5.7 inches). During the next 14 years, this lead increased to 67 percent (12.1 vs. 7.3 inches) (fig. 7). Growth rates of these trees continue to be greater with progressively wider spacing, so the differential among spacings will become greater. Largest trees on the 10 by 10 are growing at about the same rate as those on the 12 by 12.

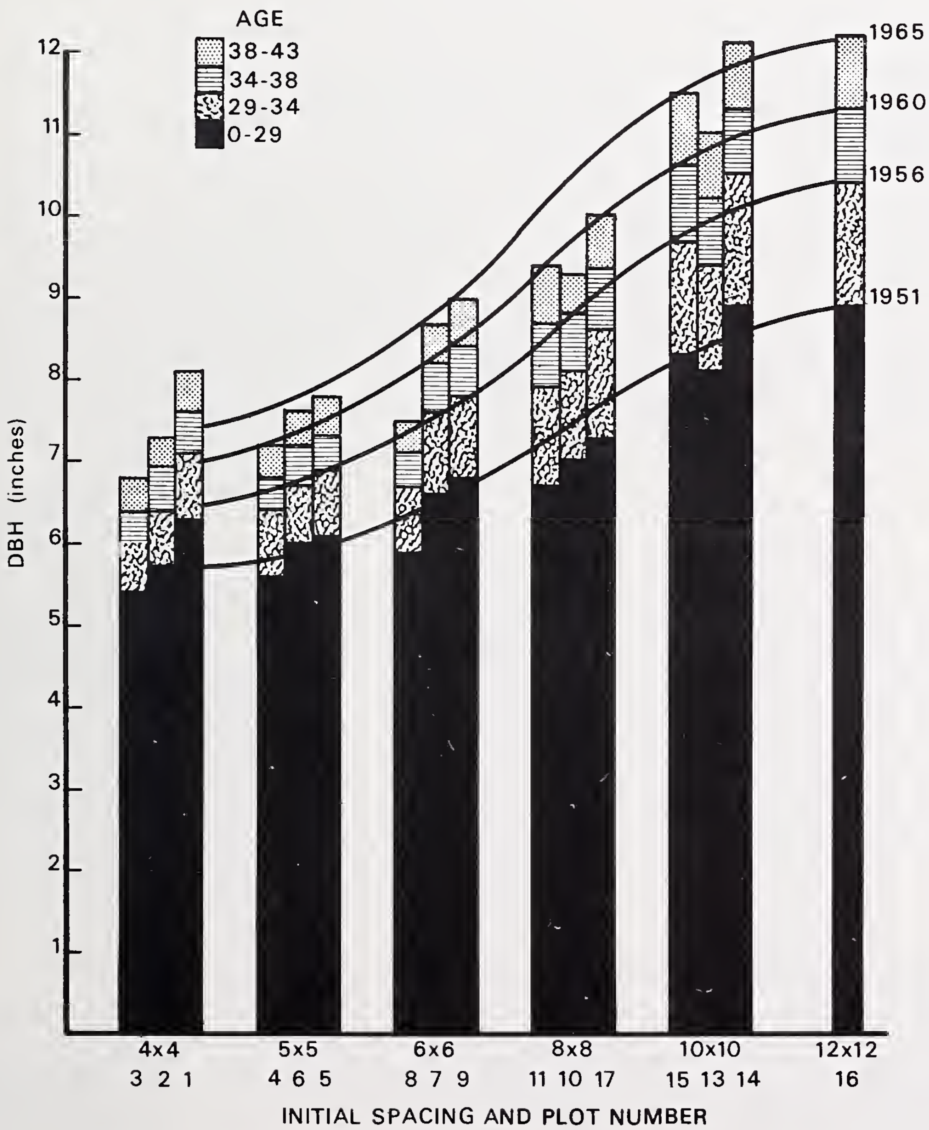

Figure 7.—Effect of spacing on average diameter growth of the 100 largest trees per acre, by periods.

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[7] Throughout this paper, average diameter refers to the d.b.h. of a tree of mean basal area (quadratic mean d.b.h.).

D.b.h. of the 100 largest trees per acre without regard to their distribution could be misleading, however, because these largest trees may occur in patches rather than well distributed over the area as commonly conceived. To assess the impact of this possibility, stem maps of each 1/4-acre plot were gridded into 25 squares, the largest tree in each square chosen, and the average d.b.h. of these well-spaced 25 trees (100 per acre) compared with those of the 100 largest trees per acre without regard to distribution (table 6). Average d.b.h.'s of the 100 largest well-spaced trees are 0.2 to 0.6 (averaging 0.35) inch less than those of the same number without regard to their distribution. Thus, if largest trees are used as a measure of productive capacity on these plots, use of a given number of largest trees without regard to their distribution leads to a slight overestimate. *Trends* in average d.b.h. of the 100 well-spaced largest trees per acre and of the 100 largest trees without regard to their distribution are very similar, however, justifying use of the latter for comparative purposes in this report.

Table 6.--*1965 average d.b.h. of the 100 largest and 100 well-spaced largest trees per acre, Wind River spacing test*

Initial spacing (feet)	Plot	100 well-spaced largest	100[1/] largest	Difference
		- - - - - - - - - *Inches*	- - - - - - - - -	
4 by 4	1	7.9	8.1	0.2
	2	7.0	7.3	.3
	3	6.6	6.8	.2
5 by 5	4	6.8	7.2	.4
	5	7.5	7.8	.3
	6	7.4	7.6	.2
6 by 6	7	8.3	8.7	.4
	8	7.2	7.5	.3
	9	8.6	9.0	.4
8 by 8	10	9.0	9.3	.3
	11	9.0	9.4	.4
	17	9.6	10.0	.4
10 by 10	13	10.6	11.0	.4
	14	11.8	12.1	.3
	15	11.0	11.5	.5
12 by 12	16	11.6	12.2	.6

[1/] Without regard to their distribution.

Although spacing effects on diameter growth are, in some respects, most meaningfully expressed by comparison of equal numbers of largest trees, effects on development of smaller trees must also be considered. These trees contribute substantially to total production on closer spacings. For example, the 575 largest trees per acre on the 4 by 4 spacing contain about the same volume as 100 largest per acre on 12 by 12 spacing. This volume (2,680 cubic feet) is partly contained in trees of nonmerchantable size in the 4 by 4 spacing (where it includes 255 5-inch trees), whereas it is all in trees 11 inches and larger in the 12 by 12 spacing (fig. 8).

How much will these currently nonmerchantable trees contribute to future yield? During the 14-year period between ages 29 and 43, many trees on the closer spacings reached a merchantable size (5.6-inch d.b.h. and larger), whereas only a few additional trees on the wider spacings moved into this size class (fig. 8). Despite this ingrowth in closer spacings, however, increase in merchantable volume was more than twice as great on the wider spacings as on the closer spacings. Also, by age 43, there were still 1,137 live trees per acre *smaller* than 5.5-inch d.b.h. (i.e., the nonmerchantable component) in the 4 by 4, compared with only 10 per acre in the 12 by 12. Thus, although many trees in the close spacings reached merchantable size between ages 29 and 43, many more trees are still smaller than the accepted minimum. Furthermore, it is unlikely that most trees currently smaller than 4.5-inch d.b.h., along with many of those in the 5-inch class, will ever reach this merchantable size. Assessment of 14-year (1951-65) d.b.h. growth of all undamaged trees in all plots shows the very slow rate of growth being made by the small trees (fig. 9).[8] Future growth will be even slower and natural mortality will remove many of these small trees.

Height

Height/diameter curves.-- Height/d.b.h. curves for all spacings at specified ages have always been very similar, indicating that effects of spacing on height growth have been nearly proportional to effects on d.b.h. growth. Thus, contrary to the commonly accepted view that height growth of dominant and codominant trees is not influenced by stand density, whereas diameter growth is, height in these stands can be fairly well predicted by diameter, regardless of stand density. Therefore, trends in diameter described previously are a preview to trends in height.

Despite the similarity among curves for the various spacings, there has been a clear trend of change over time (fig. 10). Height/d.b.h. curves at age 21 (1945) were progressively slightly *lower* with increasing spacing. Current height/d.b.h. curves are progressively slightly *higher* with increasing spacing. Thus, for a time, stand density did influence diameter growth more than height

[8] Deviations from this line show no consistent relationship to spacing of trees.

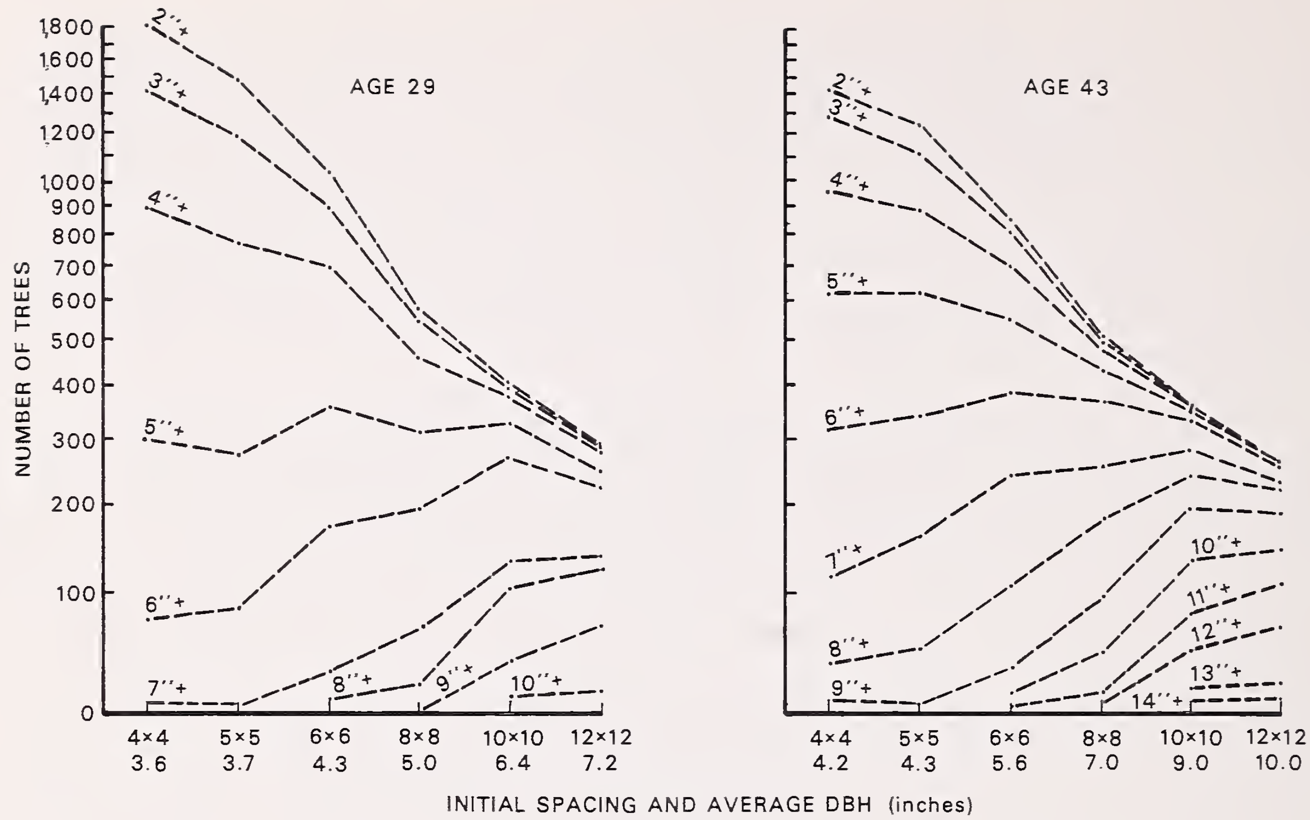

Figure 8.—Number of trees per acre larger than specified d.b.h. class at ages 29 and 43, by initial spacing.

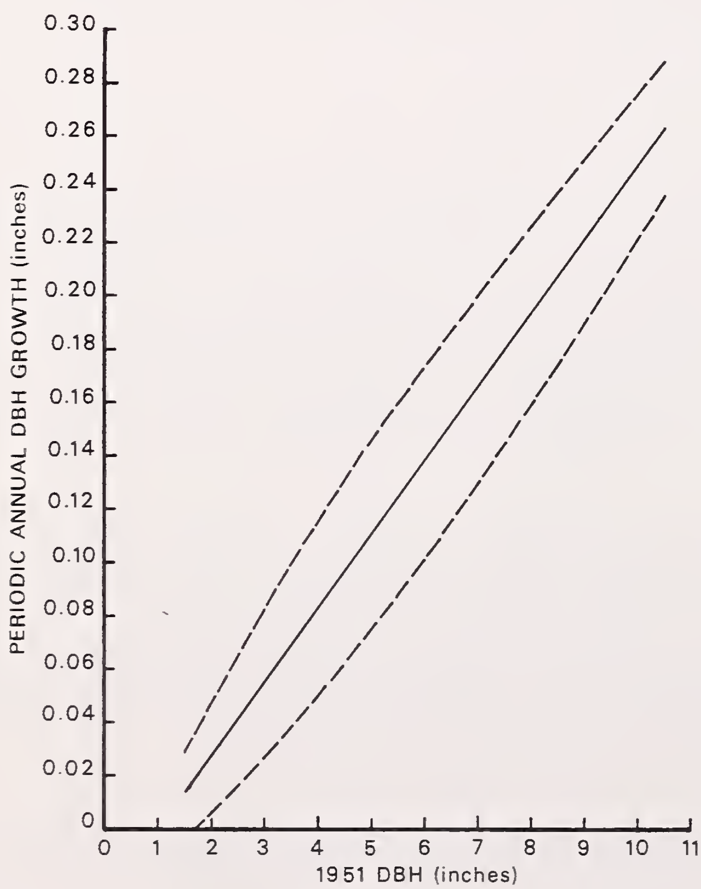

Figure 9.—Relationship of 14-year d.b.h. growth (1951-65) to 1951 d.b.h. (The band denoted by broken curves includes about 80 percent of the trees).

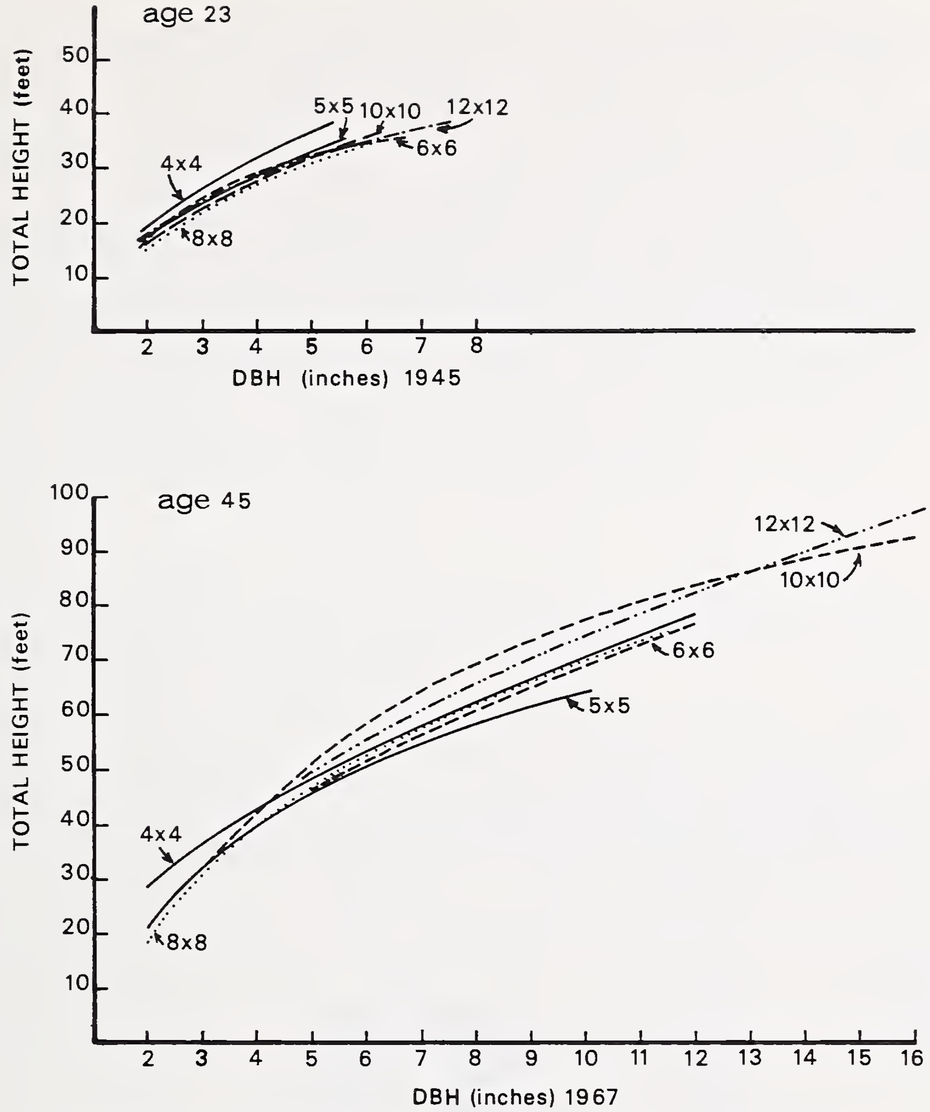

Figure 10.—Curves of height over d.b.h. at ages 23 and 45.

growth; but this is no longer true. More recently, height growth in the wider spacings has steadily improved relative to unmanaged stands (McArdle et al. 1961), whereas that in closer spacings has diminished. Height/d.b.h. relationships and comparable crown dimension/stem dimension relationships are discussed further by Curtis and Reukema (see footnote 3).

The 100 largest trees per acre.--At age 12, the 100 tallest trees per acre averaged about 12 feet tall, with those in wide spacings being slightly shorter than those in close spacings (table 7). Since that time, however, height growth of trees on wider spacings has been greater than that on close spacings. At age 29 (1951), heights of the 100 largest trees per acre in the 12 by 12 spacing were about 8 percent taller than those in the 4 by 4. By age 43 (1965), these trees were 39 percent taller in the 12 by 12 than in the 4 by 4 spacing (79 vs. 57 feet) (fig. 11).

Table 7.--*Average heights of the 100 largest trees per acre at ages 12 through 29*[1/]

Age	Spacing (feet)					
	4 by 4	5 by 5	6 by 6	8 by 8	10 by 10	12 by 12
12	12.6	12.9	12.7	9.9	11.5	10.9
17	22.3	22.3	21.9	18.6	22.2	21.7
23	32	33	34	31	37	36
29	48	44	45	46	52	52

[1/] Heights at ages 12 and 17 are for the 100 tallest trees per acre, as estimated on selected sample rows throughout the entire plantation. Heights at subsequent ages are for the 100 largest (d.b.h.) trees per acre, as estimated from height/d.b.h. curves derived from measurements on permanent sample plots.

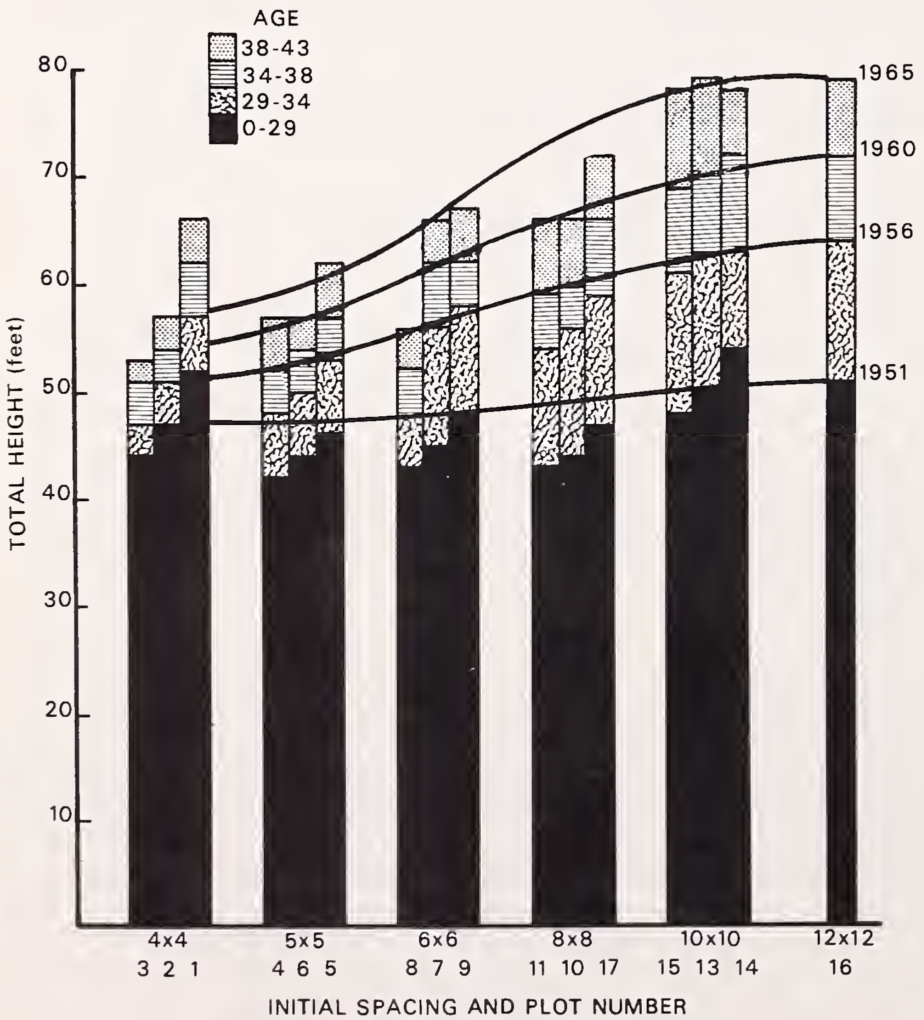

Figure 11.—Effect of spacing on height growth of the 100 largest trees per acre.

Prior to the onset of competition, one would expect about the same percent of all trees in each spacing to show superior height growth as a result of genetic and/or microsite variation. Thus, it is logical that during this period, the 100 tallest trees per acre were a little shorter in the wider spacings than in the closer spacings (table 7); these 100 trees were 33 percent of the total number in the 12 by 12 spacing, but only 7 percent of the total in the 4 by 4 spacing. That competition had begun even at an early age is exemplified by looking at the proportion of trees taller than some specified height, such as trees taller than 9.5 feet at age 12 and taller than 17.5 feet at age 17 (table 8). This not only illustrates the impact of competition on this relationship, as presumably reflected in lower percents in close spacings, but also illustrates the poorer than average condition of the 8 by 8 spacing.

Table 8.--*Relationship between spacing and tree height (acre basis); trees taller than specified height at ages 12 and 17; Wind River spacing test*

Spacing (feet)	Age 12, trees 9.5+ feet tall		Age 17, trees 17.5+ feet tall	
	Number of trees	Percent of total	Number of trees	Percent of total
4 by 4	463	17	426	16
5 by 5	364	21	317	18
6 by 6	256	21	235	19
8 by 8	46	7	65	10
10 by 10	111	25	168	39
12 by 12	85	28	139	46

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

Whereas present (age 43) basal-area yields in this trial still decrease with decreasing density (number of trees), current total volume yields (both net and gross) increase with decreasing density, and the differences, in favor of wider spacings, are increasing with time. This is the result of greater height growth on the wider spacings. Merchantable volumes, of course, increase substantially with increasing spacing. The high nonmerchantable production on closer spacings represents a substantial waste.

Virtually all damage to surviving trees and over 60 percent of mortality have been attributed to storm damage. Trees in the closer spacings have been more susceptible to such damage, especially in more recent years. Most damage and mortality have been confined to trees which have not reached a merchantable size (5.6-inch d.b.h.). Mortality and damage in the closer spacings

have tended to be clumpy and have created large openings in the stand, thus taking part of the area out of production for a substantial period of time.

Diameter growth of even the largest trees is clearly affected by spacing. The 100 largest (d.b.h.) trees per acre are currently 67 percent larger in diameter (12.1 vs. 7.3 inches) and 39 percent taller (79 vs. 57 feet) on the 12 by 12 than on the 4 by 4 spacing. These differences, in favor of the wider spacings, are also increasing with time.

These conclusions indicate considerable gains to be derived from planting at uniform, fairly wide spacing or from making early thinning to such spacing. Total cubic-volume yields on the 10 by 10 and 12 by 12 spacings in this trial are currently about 20 percent above "normal" for site 110,[9] and the difference is increasing with time. Furthermore, trees on the wide spacings are apparently of a quality equal to or better than those on close spacings. Trees on the wider spacings do not exhibit excessive taper or branchiness. Branches have died off to about the same height in all spacings and have attained only slightly larger diameter in wider spacings.

At close spacings, not only is total volume production less, but much of the production is wasted on many small trees which will never reach merchantable size. Whereas 84 percent of the trees planted at 12 by 12 spacing have reached a d.b.h. of 5.6 inches or larger, less than 12 percent of those planted at 4 by 4 spacing have reached this size. At least 20 percent of the present volume on the 4 by 4 spacing is in trees which will probably die without reaching merchantable size.

Even with wide spacings, growth of individual dominant trees has slowed down markedly. To prevent rapid decline of diameter growth rates, these stands should have been thinned. The 10 by 10 and 12 by 12 spacings could have supported commercial thinning at about age 30 and the 8 by 8 spacing could support such thinning now (age 43). Closer spacings, however, even now would not support commercial thinnings by current minimum merchantability standards.

The indicated responses are probably typical of what can be expected on most such low- to medium-quality sites. To maximize returns under such conditions, one should plant at wide spacing (10 by 10 to 12 by 12 feet or possibly wider), or make very early precommercial thinnings to such spacing in natural stands. If a market for small-sized thinning products (e.g., trees of 6-inch d.b.h.) is anticipated, probably about 10 by 10 spacing with an early start on commercial thinning is most desirable. If such a market is not anticipated, then returns will probably be maximized by planting at even wider spacing.

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[9] Height measurements in the surrounding stand, and early measurements in these plantations, indicate a maximum site quality of about 110 on McArdle's site index system (McArdle et al. 1961).

LITERATURE CITED

Eversole, Kenneth R.
1955. Spacing tests in a Douglas-fir plantation. Forest Sci. 1: 14-18, illus.

Isaac, Leo A.
1937. 10 years' growth of Douglas-fir spacing-test plantations. USDA Forest Serv. Pacific Northwest Forest & Range Exp. Sta. Res. Notes 23:6.

McArdle, Richard E., Meyer, Walter H., and Bruce, Donald.
1961. The yield of Douglas-fir in the Pacific Northwest. U.S. Dep. Agr. Tech. Bull. 201 (slightly rev.). 74 pp., illus.

Munger, Thornton, T.
1946. The spacing in plantations. USDA Forest Serv. Pacific Northwest Forest & Range Exp. Sta. Res. Note 34: 3-4.

Reukema, Donald L.
1959. Some recent developments in the Wind River Douglas-fir plantation spacing tests. USDA Forest Serv. Pacific Northwest Forest & Range Exp. Sta. Res. Note 167, 7 pp., illus.

____
1967. The yield and density aspect. Does dense spacing really produce the most volume? Western Forest. & Conserv. Ass. Western Reforest. Coordinating Comm. Meeting Proc. 1966: 23-26.

Sjolte-Jorgensen, J.
1967. The influence of spacing on the growth and development of coniferous plantations. *In* International review of forest research, vol. 2, pp. 43-94. Academic Press.

Turnbull, K. J., and Hoyer, G. E.
1965. Construction and analysis of comprehensive tree volume tarif tables. Wash. State Dep. Natur. Resources, Olympia. Resource Manage. Rep. 8, 64 pp.

Reukema, Donald L.
1970. Forty-year development of Douglas-fir stands planted at various spacings. USDA Forest Service Res. Pap. PNW-100, 21 pp. Pacific Northwest Forest & Range Experiment Station, Portland, Oregon.

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